EXTERNAL COSTS OF AQUACULTURE AND THE EFFECTS ON SCOTTISH SALMON

by

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STATEMENT OF THESIS APPROVAL

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ABSTRACT

Over the last century, wild Atlantic salmon populations have been in steep decline. Historically, fish populations have deteriorated primarily from overfishing. In the case of wild Atlantic salmon populations, the decline in the population comes from the result of spreading diseases derived from aquaculture. The crux of this thesis focuses on the aquaculture industry in Scotland, because of the rapid and unique development of the aquaculture industry and the effect it has had on wild salmon populations. This thesis will determine the costs aquaculture have had on wild salmon recruitment, as well as the costs aquaculture has had on related industries (primarily recreational angling). Through the analysis of the thesis, there will be a review of two possible policy actions that can be taken to promote abatement and maximize social welfare of the damages. The two policy actions in question will be the use of a penalty tax and the use of marketable permits by authorities.

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INTRODUCTION

Wild salmon populations have been in a sharp decline over the last century everywhere. Historically, there have been population decreases in wild salmon that have principally resulted from overfishing, but today, the population is endangered primarily as the result of an intolerable ecosystem. Although the population of wild salmon remains endangered, salmon are still available globally at grocery stores at cheaper prices than ever before and in larger quantities (Greenburg, 2010). This availability has resulted from the development of an alternative supply for salmon, which has been the modern practice of commercial aquaculture, which is also known as fish farming. The expansion of fish farming has caused a major supply shift away from fished wild salmon stocks to domesticated farm-raised salmon. This supply shift toward farm-raised salmon has caused a major decline in fishing wild salmon, but despite the decline in fishing, the wild salmon populations are continuing to decrease. The continued decline of wild salmon is primarily the result of external costs of aquaculture production damaging the environment needed to support life for wild salmon. The purpose for this thesis is to provide a background of key issues in aquaculture, analyze the effects of the external costs resulting from aquaculture production and its biological and economic effects on wild salmon, examine the sustainability of the industry, and develop an informed policy recommendation to correct the major flaws in the methods of production. This thesis will focus primarily on aquaculture in Atlantic salmon production in Scotland, because of the rapid and unique development of aquaculture in Scotland that has brought about urgent need for corrective policies.

LITERATURE REVIEW

Aquaculture has been the fastest growing food industry over the last 5 decades internationally (Liu, Sumaila, & Volpe, 2011). There has been a lot of optimism fueling the growth of the industry as the farming of salmon domestically has brought hopes of a nutritious and sustainable food source that will allow the wild stocks of salmon to regenerate. The supply shift to farmed salmon has reduced the exploitation of wild salmon populations in fishing, making it less profitable. The aquaculture industry in Scotland has been booming, as their aquaculture exports have grown 500% from 1980 to 2010 (The Scottish Government, 2012). This massive development in Scotland has brought about noticeable environmental damage that needs to be examined in great detail to determine the actual sustainability of the industry in the area as well as in other producing nations. The controllable and regenerative aspect of aquaculture has brought about superficial perceptions of a sustainable food source; the harsh reality is that perception is far from authentic. To better understand the flaws of the aquaculture industry in Scotland, it is important to understand the ecological nature of salmon and the development of the industry.

The Ecology of Salmon and Key Concepts

Salmon are a renewable natural resource with the ability to regenerate stocks over time. This essential feature implies that the wild stocks are not fixed and are variable, depending on both natural and synthetic parameters. One such natural parameter regulating the maximum stock of salmon is called the carrying capacity. The carrying capacity is defined as the maximum population that an area will support without undergoing deterioration. The growth of the wild population of salmon is limited to the capacity of the supporting environment at the maximum level due to the limited availability of resources needed for supporting life of larger populations.

Historically, salmon were a desired resource for fishermen because of the consumer demand and favorable prices. Fishermen have harvested (exploited) wild salmon for centuries to meet this market demand and have commonly made the mistake of overexploiting, with little regard for future populations. As the catch (quantity of harvest) began to exceed sustainable yields, fishermen have had to apply more effort to meet similar yields in future seasons. This is evidence of a declining population due to overexploitation, and salmon have been overfished to the point of endangerment historically (U.S. Fish and Wildlife Service, 2012). This mounting concern of dropping populations has brought about policies protecting wild salmon from overfishing, preventing extinction.

One measure of the dropping wild stock has been recruitment. Recruitment is defined as the addition to a population from all causes. There are four factors affecting recruitment in fish stocks: death in the living stock, birth of next-generation stock, emigration, and immigration. The losses to the wild salmon stock can be analyzed by reviewing its recruitment to see if the new juvenile fish are able to replenish the previous generation. Salmon have unique behavioral characteristics that make understanding their recruitment rather difficult.

Salmon are an anadronomous fish. An anadronomous fish is one who is hatched in fresh water but adapts to sea water to migrate to the ocean (Organization for Economic Co-operation and Development [OECD], 2004). Salmon feed in the sea and each year, some of the salmon may return to the freshwater breeding grounds to breed. The salmon who return to the breeding grounds are known as grilse if they return to spawn after spending just 1 year at sea, and are characterized by their smaller size than full grown salmon that may spend 1 to 2 years at sea feeding (des Clers, 1993). The grilse return to the breeding grounds by migrating up fresh water streams to mate and reproduce. The female fish lay noticeable orange roe (eggs) that are fertilized by the males and then buried in the gravel of the riverbeds and lakes. Roe hatch and are then called fry, as denoted in Figure 1. Fry then mature to become parr, and remain in the fresh water until they mature enough that they become tolerant of saline water, which can take 1 to 4 years. Once the parr are tolerant of saline water they migrate to sea at a life stage known as smolt and remain smolt until returning to freshwater for breeding as either grilse (which spent only one winter at sea) or mature salmon (which spent two or more winters at sea). Predation in the freshwater areas is common by birds, bears, and mankind. Natural predators target female spawning fish and their nutritious roes. It has been found that about 1% of roe survive to juvenile ages after accounting for starvation, disease, and predation (Greenburg, 2010).

Beyond the age of 2, salmon are considered to be market size and fishermen typically retain them for harvest. Parr that have not yet gone to sea for food at the age of 2 are considerably smaller, because salmon gain considerable size from their activity at

Salmon Life Cycle

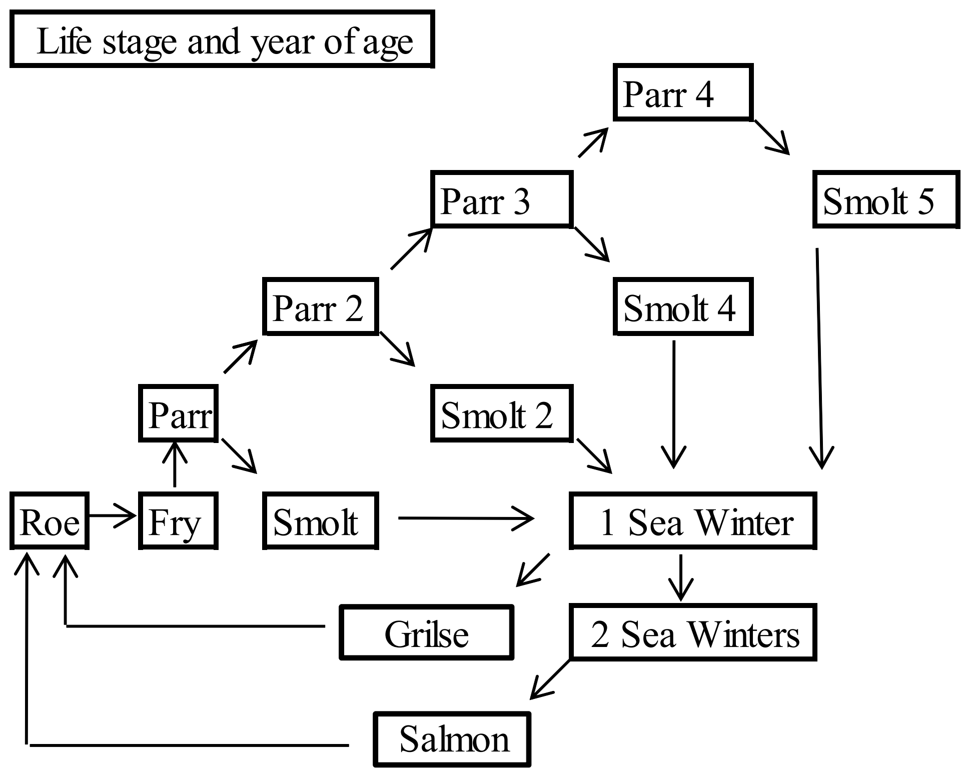

Figure 1: The life cycle of Atlantic salmon (OECD 2004).

sea. Once at sea, smolt typically feed on krill and capelin, which give them a natural pink meat that is rich in omega-3 fatty acids (OECD, 2004). Their diet is what makes them desirable to consumers, as the fatty acids are appealing in taste and also help prevent cardiovascular disease.

There are several species of salmon, with several species native to the Pacific Ocean and one species (Salmo salar) native to the Atlantic Ocean. The Atlantic salmon typically meet near Greenland for feeding and return to spawning grounds from which they migrated. The Atlantic salmon migrate as far south as Spanish rivers, but the majority of the population has historically returned to Scandinavia or Canada for spawning. Pacific salmon species typically feed in the Bering Sea and return to the native spawning grounds as well. Pacific salmon spawning grounds can be used to identify subspecies since salmon will return to the same place they were hatched. As part of an action to aid the growth rates in the wild population, the United States introduced hatcheries in Alaska in 1971 (McGee, n.d.). The abundance of salmon in Alaska is still protected from commercial fishing, although recreational fishing is seasonally permitted as well as sustainable fishing (harvesting by rural populations). Without farmed salmon, the demand would be unsustainable and would lead to extinction if wild salmon catch remained constant.

Salmon require cold, oxygen-rich water to complement their aggressive swimming patterns. They are predators in the wild and must have access to the freshwater grounds they were hatched in for breeding. In New England, dams on rivers, as well as run-off agricultural pollution, have been a major cause for population losses. The polluted rivers and dams prevent the salmon from re-entering breeding grounds and as a result, the entire regional population dies without being able to reproduce (Greenburg, 2010). Salmon have also discontinued migration to rivers that have been cleared of surrounding forests. Salmon prefer shaded and covered rivers for their migration to breeding grounds. Although these actions have been fatal to regional populations, they have not been a major factor in the depletion of the overall global wild stocks. The regional losses to salmon populations have caused bigger concerns over biodiversity as subspecies are dwindling due to these regional problems (Greenburg, 2010).

Ecologists believe that the salmon population had a relative peak around WWII as commercial fishing areas were untouched (Greenburg, 2010). With the fishing hiatus, the wild salmon stocks were able to grow to the maximum level of the carrying capacity for the environment. Following the war, there was a surge in fishing as salmon populations were abundant. Competition was building in the harvest of wild salmon and subsequent annual harvest levels continued to exceed sustainable yields. As harvest levels began to drop, the prices for salmon began to rise and consumers began losing access to salmon in some areas. Commercial fishing began to become unprofitable as a result of diminished catches and many fishermen exited the salmon industry. This created an opportunity to supplement the supply for salmon through domesticated farms. Commercial aquaculture farms began developing to create an alternative supply for salmon to consumers in the late 1960s and early 1970s and have continued to increase production. Figure 2 reflects the abundance of annual salmon runs in Scotland over time.

Recently, the slide in salmon population has been found to be the primary result of widespread diseases that were spreading globally rather than dam-building and fishing. Viral diseases, bacterial diseases, and parasites were all found in many wild salmon populations as the main factor in their high mortality. The most prevalent diseases found in the wild population were salmon anemia and sea lice. Salmon anemia was causing disorders in fish and it was a deadly disease primarily off the coasts of Canada and Europe, with mortality rates reaching up to 100% of populations in some cases (Cottet, Cortez-San, Tello, Olivares, Rivas-Aravena, Vallejos, Sandino, & Spencer, 2010). Sea Lice is a deadly parasite that also has high mortality rates (approximately 80%), primarily

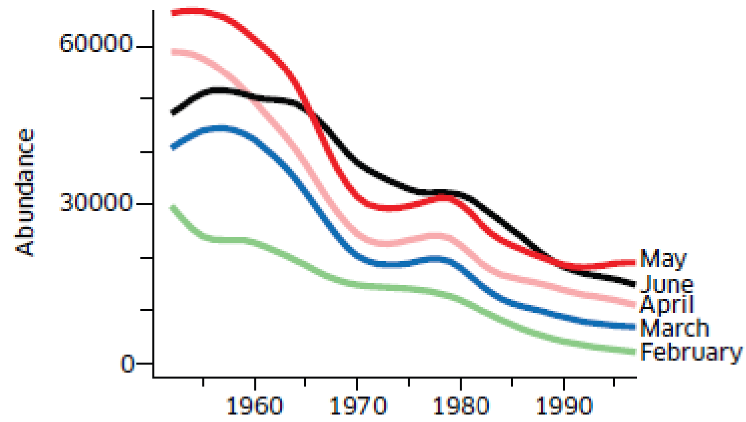

Figure 2: Wild Atlantic salmon runs in Scotland over time. Captured from the Scottish Government

in juvenile fish (Krkošek, Ford, Morton, Myers, Lewis, 2007). Other diseases were prevalent as well in many wild salmon stocks, including Herpes Virus, Furunculosis, Sprolegnia, Gyrodactylus, etc. (des Clers, 1993). Some diseases were treatable in a few cases, but, with the diseases spreading through the wild population subspecies as salmon congregated at common feeding grounds, international concerns developed for the long-run populations of all wild salmon. As we will find out below, these diseases have been derived from the current methods practiced in aquaculture.

Methods and Development of Aquaculture

While the wild salmon stocks were sliding, the aquaculture industry was booming. Norwegian fishermen developed the primary method for modern salmon farms in the beginning of the 20th century. Norwegian fishermen were the first to begin catching Atlantic salmon near Greenland and bringing them back to the Norwegian coast to raise and feed in offshore nets (Greenburg, 2010). This method was very successful and producers began incorporating breeding of the farmed fish to hatch the next generation of farmed population. Fish were now being hatched in on-shore hatcheries, raised until juvenile ages, then transported to off-shore nets to be raised until harvest or to be brought back to the hatchery for breeding when fully mature. Norway's success became known to other nations, who entered the market using similar methods, including the United Kingdom, Canada, and Chile.

This method of off-shore pens brought great success to the producing countries that have geographical advantages for production. Norwegian fjords, Scottish lochs, and Canadian and Chilean inlets were ideal locations for the farms. The inlets protected the farms from strong waves and heavy wind and the gentle current in the inlets helped to aerate and clean the farms. The inlets had cold, oxygen-rich waters with a supporting ecosystem that were very suitable for the farmed salmon (Paisley, Ariel, Lyngstad, Jónsson, Vennerström, Hellström, & ØStergaard, 2010). Farmed salmon production first exceeded wild salmon production in 1998 (Liu & Sumaila, 2010). Today Norway is the largest producer, followed by Chile, Scotland, and Canada. Norway has also been the largest investor between two major firms, Cermaq and Marine Harvest, who own major operations in all producing countries (Paisley et al., 2010).

In early stages of aquaculture, the salmon were fed trash fish, fish offal, slaughterhouse wastes, capelin, and herring. This method resulted in a less nutritious fish than a wild fish. Producers also added chemicals to the feed that would turn the salmon meat pink to replicate the meat recognized in wild salmon (Paisley et al., 2010). Today, the salmon are fed pellets composed of fishmeal, fish oil, wheat, corn, gluten, and legumes to make the farmed salmon's nutritional composition roughly similar to that of wild salmon. Today in Scotland, the price for a wild salmon is still about 6 times higher than the price of a farmed salmon (NASCO, 2008).

Aquaculture producers took steps to change the genetic structure of the farm-raised fish to make the process more efficient. The farmed-raised salmon in existence today are very different than their wild Atlantic cousins. Domesticated livestock and poultry have been bred for their favorable characteristics using the genetic breeding design developed by geneticist Jay Laurence Lush (Greenburg, 2010). Domestic salmon production has developed the same way domestic poultry and livestock production has been genetically designed. Norwegian geneticist Trygve Gjedrem has bred domesticated salmon based on their proficient metabolisms and today, a domesticated salmon grows three times the rate of its wild cousin (Greenburg, 2010). This development has had great benefits as salmon are now more efficient than any livestock or poultry in terms of feed to conversion ratios. Today's domestic salmon takes 120 grams of feed to produce 100 grams of salmon. Each generation of salmon has improved approximately 14% in growth rates since aquaculture was first developed, signaling room for further improvements (Greenburg, 2010).

Aquaculture has certainly had positive benefits that have been generated from its development. The improved access to efficient and nutritious food globally has been very important in terms of fighting hunger and cardiovascular disease. Other benefits that have been generated from aquaculture have been the new access to salmon all year round. Salmon are no longer seasonal and are available at grocery stores year round at cheaper prices.

In addition to the benefit of salmon availability to consumers in aquaculture, the development of aquaculture in Chile has helped the Chilean economy develop in rural areas by giving Chile access to a profitable export. Chilean producers became the second largest producer in 1992 with the support of foreign direct investment in Chilean production from Norwegian shareholders (Bjørndal et al., 1999). Chile has been able to gain market share with very little domestic demand for salmon and as a result, Chile is heavily dependent on foreign consumption of their exports. Salmon farms in Chile are located in the southern tip of the country in extremely rural and historically poor areas. Although salmon are not indigenous to Chile, the large clean coastline and cold waters with ideal salinity give Chile an advantage in production. Chile has had great success as their production cycle is the opposite of their competitors in the northern hemisphere, which allows them to supply salmon in the off-season in the north. Chile exports primarily to the US and Japan and their success has allowed for them to build the infrastructure to transport the fish to grocery stores within 48 hours (Greenburg, 2010). There is low demand for salmon with Chilean consumers, so this industry has developed purely for the reason of exporting.

Salmon aquaculture has certainly had its benefits in nutrition, resource accessibility, trade, and developmental economics, but this has all come at a great cost. The methods used in aquaculture are flawed and the costs have great effects on the environment. This next section will review the costs associated with aquaculture in detail.

Costs and Damages of Aquaculture

The costs associated with aquaculture are very significant and will continue to worsen without better policies. The biggest cost that has been associated with aquaculture has been its negative effects on the wild population of salmon. As mentioned before, wild salmon populations are continuing to slide and the reason for the slide has been the spread of infectious diseases, which are derived from aquaculture. The most expensive costs derived from aquaculture have been the increases in the evolution of new diseases, the strengthened deadliness of all diseases on salmon species, and the pace at which they are transmitted to the wild populations.

The location of the salmon farms in fjords, lochs, and inlets are locations right in the migratory path for wild salmon. Wild salmon/grilse returning to spawning grounds pass by the farms and later in the season, juvenile smolts pass by the farms on their way to the feeding grounds. The wild salmon come in close contact to the domesticated salmon farms and this has been the major issue. Sea lice and other diseases are very common on salmon farms due to the dense populations of fish. The diseases are incubated on the farms and when the wild salmon pass through the area they become infected. The level of diseases in wild salmon derived from farmed salmon is 73 times greater in wild populations migrating near the salmon farms on their annual run to spawning grounds or to feeding grounds (Krkošek & Volpe, 2005). This transmission of diseases like sea lice and salmon anemia are deadly to the wild populations, especially with vulnerable young salmon. Salmon farming has been banned from 21 out of 37 available fjords in Norway to protect the regions from the spread of disease (Paisley et al., 2010). Unfortunately, the damage has already affected the wild population in the closed regions and is possibly irreversible. The action to close infested regions does not retroactively fix the sunk costs already incurred in the regional environments.

Domesticated salmon are escaping the farms each year in high numbers as well (Greenburg, 2010). Since the domesticated salmon have been bred for their size, they have a competitive advantage in relation to their wild cousins in hunting and in mating. The domesticated salmon have been captured in Scotland on their way up to the breeding grounds with the wild populations. This raises concerns over the protection of the regional species and also the biodiversity of salmon. The genetics of the regional species can be jeopardized if the domesticated salmon successfully breed with the wild continuously (Greenburg, 2010). Also, the size advantage of the domesticated salmon gives them the ability to outcompete for food and can lead to starvation of wild salmon schools sharing the feeding grounds. The Scottish Ministerial Group on Aquaculture authorities recognized escaped salmon as a major problem and has now taken political action with an initiative in 2009 to improve containment of farmed salmon. The ministerial group required aquaculture producers in the industry to report escaped fish to the Ministry immediately upon occurrence. Failure to report to the ministry may result in an offense that can lead to the revocation of licenses (The Scottish Government, 2012). The need for this initiative came as a result of the large numbers of escaped fish, as displayed in Figure 3.

Aside from the damages affecting the wild populations of salmon nearby, the local ecosystems are also being damaged from the farms. The locations of farms in fjords allow for the natural cleansing of the farm, but salmon farms have very high waste levels that can be deadly to the local ecosystem. Excess feed and salmon waste release high

Figure 3: Escaped farmed salmon from the Scottish Government in 2012

levels of nitrogen that have been causing algae blooms. Algae blooms can destroy all life in an area, causing dead zones that cannot support life and, according to Greenburg, the dead zones are in some cases 10 times the size of the farms themselves. Algae blooms come as a result of the nitrogen and phosphorous that is a large byproduct from production (Burridge, Weis, Cabello, & Pizarro, 2008; Liu & Sumaila, 2010).

Additional damage to the environment has also occurred as a result of treatment of pathogens. To combat diseases, farmers are using antibiotics and therapeutants in their feed to treat the salmon. The first major damage that results from the use of antibiotics is the introduction of the antibiotic to the local environment (directly in their introduction to the farmed salmon diet, and indirectly through the byproduct of salmon digestion). Antibiotics are typically still active in the salmon's stool (Burridge et al., 2008). Also, uneaten food falls directly to the ocean floor and into the ecosystem (op. cit.). Antibiotics are known to be lethal to organisms needed to support life, like phytoplankton and zooplankton. The biggest risk with these applications is the development of mutating bacteria that can worsen diseases both in salmon and in humans (Burridge et al., 2008). There is also the risk that undigested antibiotics will make their way to the consumer of the salmon, extending the antibiotics exposure beyond those already exposed at the farms (employees and local residents). In Chile, entire farm sites have been lost when the antibiotic exposure killed all organisms needed to sustain life. Chile uses significantly more antibiotics than any other producing nation, which causes concerns about effective oversight in the area (Burridge et al., 2008).

Additional concerns in the development in aquaculture have been raised with the development of the first genetically modified salmon. The AquAdvantage salmon is the first genetically modified (GMO) salmon. It has been developed by AquaBounty. AquaBounty's GMO salmon is heavily regulated, with strict oversight. The AquAdvantage fish are for the most part sterile females that must be raised in on-shore tanks (Palfreman, 2001). AquaBounty found funding by offering an IPO on the London Stock Exchange, but AquaBounty has had very little success. AquaBounty has also failed to get approval in any area to raise GMO fish in off-shore nets as regulators see major risk with even small amounts of escaped fish causing a catastrophe to the wild populations (Palfreman, 2001). The GMO fish grows at twice the rate as a standard farm fish according to AquaBounty, which would be deadly if a GMO salmon were to escape and breed in the wild. Regulators are also concerned with the risk that diseases currently affecting farmed fish will mutate and infect GMO fish and create a deadly epidemic in salmon (Palfreman, 2001). AquaBounty financial statements show that there has been little success in this industry, which is primarily because this industry is still in its infancy, coupled with the lacking social support for GMO products (Figure 4).

Sustainability Concerns in Scotland

Scotland has been very successful for the better half of a century in the aquaculture industry. Currently, the Scottish government reports 78,611 tons were exported in 2010 and the industry generates approximately 6,200 jobs, including supporting industries. The optimism in Scotland is fading when looking at recent data. Researchers believe Scotland's current production levels are unsustainable (Liu & Sumaila, 2007). Scotland's wild salmon population has been sliding for almost a century and it is largely due to the high density of fish farms. From 1980 to 2005, the wild harvest in Scotland has dropped 66% (Liu & Sumaila, 2007). Scotland has had disease outbreaks

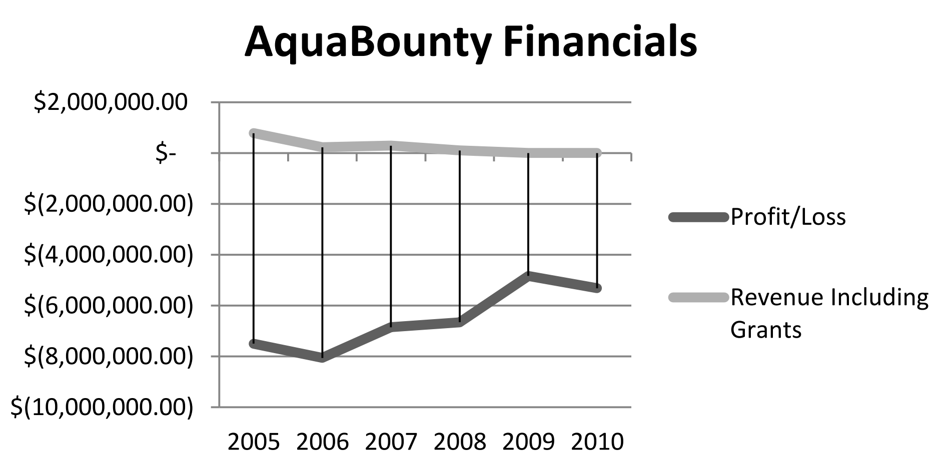

Figure 4: Financial data captured from AquaBounty Financial Reports

causing major productivity losses in the sector, particularly from sea lice. Scotland's suitable sites along the coastline are almost fully employed, leaving little room for expansion (Liu & Sumaila, 2007). Figure 5 shows all of the farm sites currently in operation, as reported by "Stand up for Salmon" conservationists. The industry in Scotland may risk losing competitive ground with dwindling resources, and without the proper policies, the damages of aquaculture may be fatal to the regional populations of wild salmon.

The Scottish government has set a goal to bring the wild stock of salmon back to the maximum sustainable stock by 2015 and this goal may be difficult with the wild populations continuing to drop (The Scottish Government, 2012). It is important for Scotland to evaluate its resources and take immediate policy action in order to make a

Figure 5: Map of Scottish farm locations captured from The Salmon and Trout Association. Each farm site is denoted by a blue pin.

reasonable attempt at reaching the goal by 2015. There are alternative methods of production that can be applied with less pollution using on-shore facilities or using a sea-bags rather than an open net. These methods would prevent the environmental damages resulting from the traditional methods, but researchers like Liu, Sumaila, and Rashid suggest that with the current policies in place, those methods are unprofitable under the current market conditions (Liu, Sumaila, & Rashid, 2007). Policies in competing countries allowing current methods of aquaculture have caused many producers to neglect any attempt to pursue cleaner methods.

Bio-Economic Theory

Economists have historically analyzed fish populations for the primary reason of optimizing their economic value in short-run and long-run economic equilibrium based on the harvest of fisheries. Alfred Marshall (1890) termed renewable natural resources "living capital" for this very reason. The combination of analyzing the economics and biological nature of living capital has often been termed bio-economics since there is a deep relationship between natural biological characteristics of fish and the economic yield resulting from harvesting their useful values as living capital. Alfred Marshall described the renewable phenomena of natural resources like fish in Principles of Economics as a function of the rate at which renewal is dependent on the amount of the resource left unharvested to perpetuate itself.

Alfred Marshall introduced the Economic Law of Diminishing Returns, which in simple terms stated that by increasing inputs of production, there will be at some point a diminishing return in output per unit of input. According to Milner Schaefer (1957), economists debated whether this law applied to fisheries. In early methods of fishing, the amount of effort applied to fishing was insignificant and the methods of fishing were rather inefficient, so they seemingly had no effect on the yield per unit of effort. As fishing methods became more efficient in the 20th century, Milner Schaefer noticed that there were very different bio-economic laws affecting returns per unit of input on fisheries that resulted from the complex changes in fish populations.

H. Scott Gordon and Milner Schaefer separately developed key bio-economic models for fisheries to help create a better understanding of dual equilibria that occur in both the marketplace and the ecosystem that result in varying returns (Gordon 1954; Schaefer 1957). One primary concern for fisheries economists was the need to better understand individual resources' natural equilibria. The natural equilibrium as described by Schaefer is that populations neither fall nor rise over longer periods. Schaefer noticed that over long periods of time, losses to populations are balanced with new accessions and additions are balanced by losses. This natural equilibrium as described by Schaefer is at its maximum when it reaches the carrying capacity of the environment. Schaefer modeled growth rates of fish stocks over time as well as a model of the population growth denoted in Figure 6 and Figure 7.

Schaefer added economic principles to the biological models to create a simplified bio-economic model. He analyzed models of open-access fisheries operating in perfect competition, and also centrally managed fisheries. Schaefer pointed out that by looking at the curve for surplus stock (Figure 6) and incorporating the economic models for profit and harvest under different management policies, there can be a simultaneous

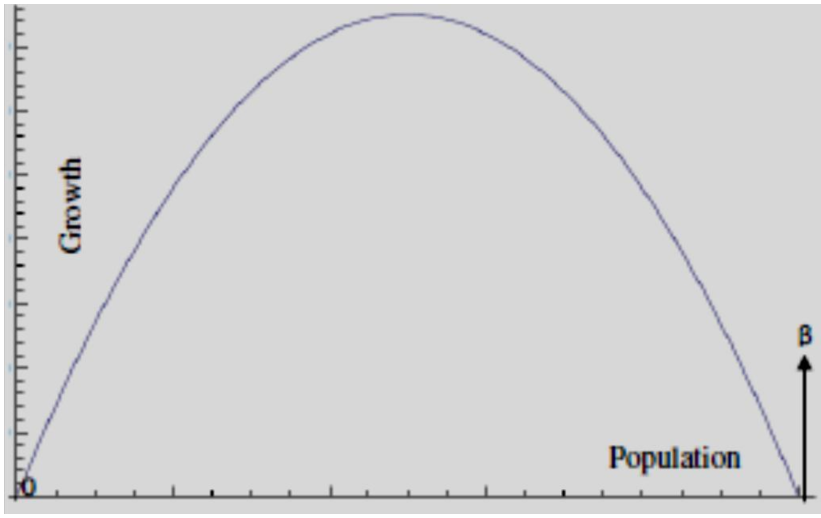

Figure 6: The figure is a model showing the growth of salmon at different population sizes. Growth rates slow at larger population sizes until reaching point β, which is the carrying capacity for the environment. The continuous formula for the curve is $\frac{dx}{dt} = G(X_t) = \alpha X_t * (1 - \frac{X_t}{\beta})$ where α is intrinsic growth, X_t is the stock population, and β is the carrying capacity

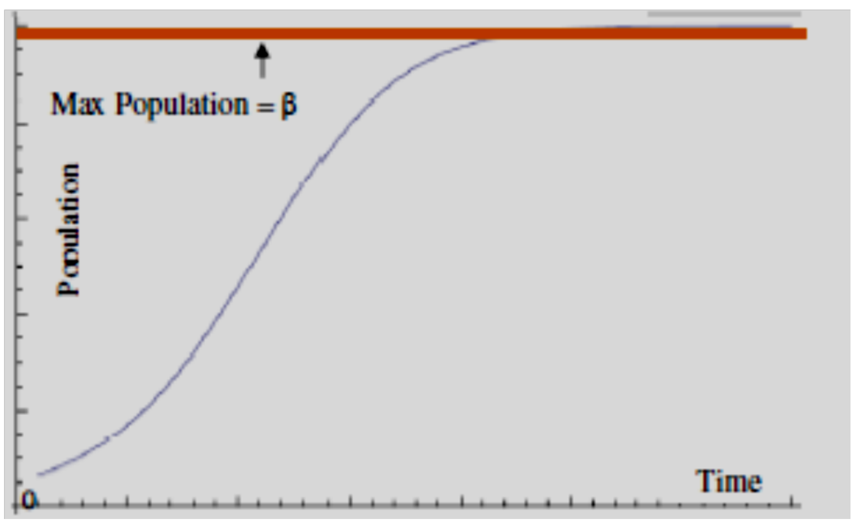

Figure 7: Shows the growth of a population over time. This is known as the time path growth curve, which we see reaches a maximum at β, denoted by the orange horizontal line. The discrete formula for the curve is $X_{t+1} = X_t + G(X_t)$

biological and economic equilibrium. One such management policy results in overexploitation. It is denoted in Figure 8 by point OAQ (policy of open-access fishery).A policy with maximum economic yield is denoted in Figure 8 at point MEY (centrally managed fisheries). Each of the loci marked OAQ and MEY differ not only in management policy but in the different economic results. The surplus growth for a stock in Figure 8 is also called its sustainable yield as it is the level of harvest that can be extracted from the fish without reducing the base of the population itself.

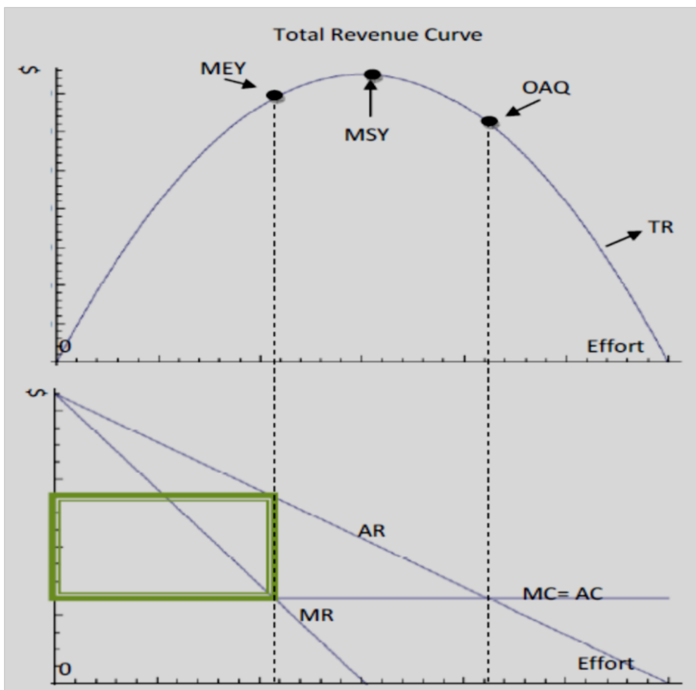

Figure 8: The curve on the top is the surplus curve, or sustainable yield multiplied by the price of fish to find total revenue or TR in the steady state, the formula is $\boldsymbol{TR = P * [\alpha X_t * (1 - \frac{X_t}{\beta})}$ where P represents price, OAQ represents Open Access Equilibrium, MSY represents maximum sustainable yield. The curve below shows AR which is average revenue or the formula $\boldsymbol{AR = \frac{TR}{X}}$. MR (Marginal revenue) is the formula $\boldsymbol{MR = \frac{\partial y}{\partial x} = P * [\alpha X_t * (1 - \frac{X_t}{\beta})}$. TC (total cost) is the formula $\boldsymbol{TC = E * C}$ where E is effort and C is cost per unit of effort. MC (marginal cost) curve is the formula $\boldsymbol{MC = \frac{\partial y}{\partial x} = E * C}$. The green box denotes the amount of profit under a centralized management policy at MEY

Gordon pointed out that there is a policy goal to find the optimal degree of utilization that maximizes the net economic yield (difference of costs and revenues) and simultaneously maximizes the exploitation of the stock (Gordon, 1954). Gordon pointed out that uncontrolled exploitation of common property fish stocks leads to extraction beyond the maximum sustainable yield. Management must aim to promote MEY rather than allow for OAQ to be reached (Gordon, 1953).

Schaefer's model brought dynamic additions to earlier models created by economists like H. Scott Gordon and Anthony Scott. Schaefer's growth curve reflects the net effects on a populations' growth rate resulting from recruitment, growth, and natural mortality. Population dynamics in fisheries are far more complex and assuming so many factors to be incorporated in the sustainable yield curve was a major flaw. To compensate for the simplicity of Schaefer's model, W.E. Ricker (1954) developed an improved model for understanding population dynamics, commonly called the stock-recruitment model. As mentioned earlier, Merriam-Webster defines recruitment as the addition to a population from all causes. Ricker's model for recruitment accounted for more clarity of density-dependent populations in understanding the recruitment resulting from a spawning biomass. The Ricker formula for stock recruitment is:

$$R_{0.t+1} = R_{a,t}e^{\alpha(1-\frac{R_{\alpha,t}}{\beta})}$$

The model is a nonlinear domelike curve whose apex reaches maximum recruitment capacity when the slope of the curve reaches zero, which is denoted as β in Figure 9. The 45 degree line crossing the model represents replacement in Figure 9.

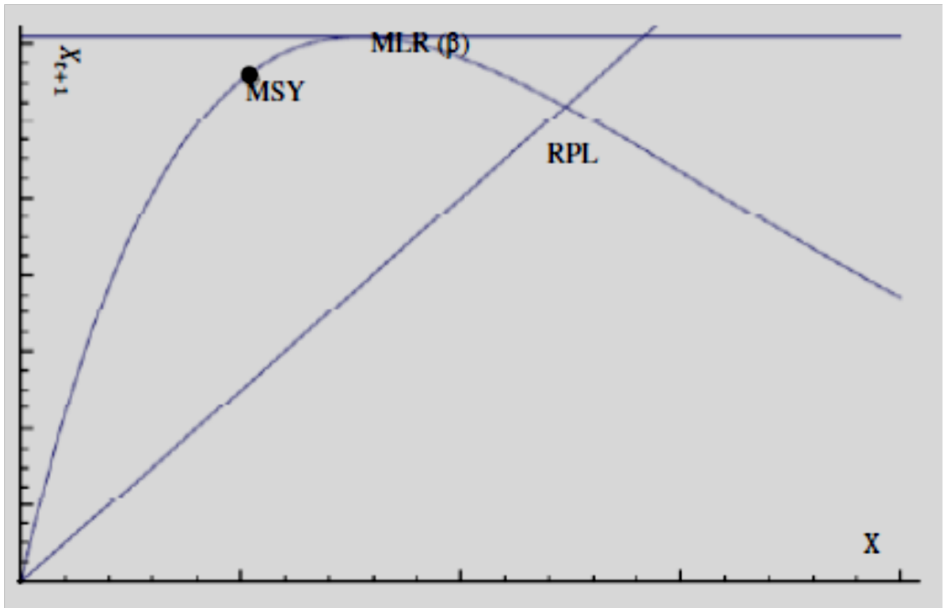

Figure 9: Ricker's model for recruitment. RPL represents replacement

Where the recruitment curve intersects the 45 degree line, there will be exact replacement of the spawning biomass in the level of new recruits (point RPL). The area above the 45 degree line is the sustainable yield. It is maximized when the slope of the recruitment curve is parallel to the replacement line, as denoted in point MSY.

<u>Methods for Valuing External Costs and Policies</u>

The external costs related to the production of aquaculture have significant effects and it is important to correct these costs. The external costs from aquaculture are negative external costs that affect a delicate ecosystem, and without correction, there can be irreversible damage. In order to make optimal corrections, it is important to find a monetary measure for the external costs. These external effects are not reflected in the market price for salmon and therefore, the market for aquaculture is not operating efficiently since there are costs not being incurred by the producers. By finding the economic value of the damage caused, policy actions can be taken.

An externality is generated when an economic activity generates damages that affect other individuals of society. The externalities from aquaculture at this point can only be corrected if regulations are implemented to minimize the loss of welfare. “Coase Theorem” was an idea by Ronald Coase (1937) in which market imperfections from externalities would automatically self-correct because there would be bargaining between the polluter and those affected to optimize the social welfare. In order for the Coase Theorem to prevail, the transaction costs to bargain must be less than the social benefit. In aquaculture, this has not happened and it appears it will not happen in the foreseeable future, and this may be the result of costly legal fees to reach a bargaining arrangement. It is important for regulators to determine the optimal external costs from aquaculture in turn to create a maximum social benefit by enforcing the best policy. Since the costs of aquaculture are “nonmarket costs,” it is important to first measure these costs as an estimation of economic/monetary damage. Only once the costs are accurately valued can an optimal regulation be implemented to maximize the total social welfare. A nonmarket cost is a cost affecting a product with nonmarket value (Nonmarket Value, n.d.). Products with nonmarket value are valuable goods and services that are not traded in the market. A good example of a nonmarket cost would be clean water. Clean water has no market value because it is not traded in the market, but is necessary for society and is therefore valuable.

By determining the monetary value of external costs generated through aquaculture production, a damage function can be generated that can be used to construct optimal policies. The damage function indicates how pollution damage varies at different levels of output and at determined monetary costs, and is also referred to synonymously as an external cost function (Pearce & Turner, 1990). The social inefficiencies resulting from external costs create a deadweight loss in social welfare. By determining the net private benefit generated from production, a social maximum can be found when the first derivatives become equal, as depicted in Figure 10.

It is important to recognize that this evaluation of the external costs can be costly to regulators as it often requires detailed research and there is also possible asymmetric information about the polluter that regulators and society may not be aware of. Although there are these costs and risks arise, it is still necessary to evaluate this damage to create a social optimum. Figure 10 is an example of the deadweight loss that results from this production. For Scotland and other aquaculture producing nations, property rights are clearly defined by law (Scottish Government, 2012). Under the defined property rights in Scotland, no producers (not just aquaculture producers) have the right to use the environment for waste disposal greater than the standards as defined by the SEPA (Scottish Environment Protection Agency). The producers also have no property ownership of the wild salmon population that are affected by their outputs (Scottish Statutory Instruments, 2011). Some standards set by the SEPA are often intended to estimate the aggregate assimilative capacity for the Scottish natural environment. The assimilative capacity is defined by Webster (n.d.) as “The ability of a body of water to cleanse itself; its capacity to receive waste waters or toxic materials without deleterious effects and without damage to aquatic life or humans who consume the water.” This is ultimately damage that can be tolerated by the environment and society. For Scotland, the

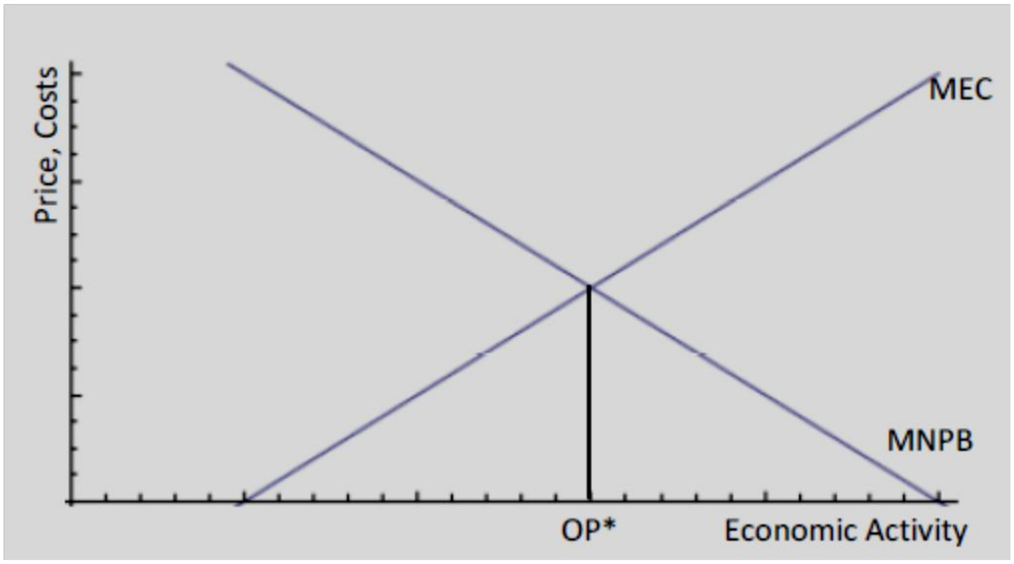

Figure 10: As mentioned in the case of aquaculture, without regulation, there will be very little chance that society will reach the Pareto optimum. When we view this reflection on the market for Atlantic salmon, we can see a reflection of the deadweight loss that is prevalent in society since the absence of a policy results in economic activity where the MNPB intersects the abscissa. Welfare is maximized at OP* and a movement from the intersection of MNPB and the abscissa to E* is a Pareto improvement that results in the Pareto maximum

SEPA's standards only regulate uses of antibiotics in the environment (Scottish Statutory Instruments, 2011). Scotland has set guidelines for disposal of other benthic nutrients, but unfortunately, the guidelines are not enforced as standards on aquaculture producers (op. cit.).

To determine the damage function/external cost function, there must be a monetary value associated with the pollution over different levels of economic activity. To monetize these external costs, there are several methods that are commonly used. The social value of the costs must be known or estimated in order to maximize social economic welfare. The methods applicable to aquaculture are market-pricing, hedonic pricing methods, abatement/replacement costs, and contingent valuation. Once we have a monetary value, a policy can be generated to bring society closer to E*.

Nonmarket Valuation I - Market Pricing Method

Market pricing method for evaluating external costs involves looking at the prices for market goods and service affected by damage from a polluting economic activity (King & Mazzotta, 2000), since prices measure the quality and quantity of a uniform good or service. In the case of aquaculture, an algae bloom may destroy a resource that has economic value once harvested. Fisherman would not be able to harvest resources in the proximity and this fall in supply caused by the presence of aquaculture would likely cause a spike in the price. A higher price for the good reflects a diminishing consumer surplus and a clear presence of a monetary cost of aquaculture.

The benefits in the market pricing method are the ease of capturing the cost, the availability of market information, and well-defined market values accurately reflecting social preferences. The market pricing method does lack dynamics needed to capture full external costs since not all externalities are manifested in the marketplace. Market prices for affected goods may not capture the full effect of the costs and also the algae blooms affects organisms that may not have a clearly defined market price (like plankton). Although plankton have little value in direct consumption, they serve a valuable purpose in supporting life in the Ocean. Also, since fishing is seasonal, it is difficult to fully grasp the total effect on the price as supply amounts fluctuate. This method reinforces the "polluter pays principle" which is defined by the OECD (2001) as "the principle according to which the polluter should bear the cost of measures to reduce pollution according to the extent of either the damage done to society or the exceeding of an acceptable level of pollution." Policymakers would find it important to see to it that those causing the loss in welfare reimburse the lost surpluses to economic agents affected.

Nonmarket Valuation II - Hedonic Pricing Method

Hedonic pricing estimates economic values for an ecosystem and its direct effect on market prices (Pearce & Turner, 1990). Hedonic pricing commonly evaluates economic impacts on real estate. Real estate has both internal characteristics and ambient characteristics affecting its price. Coastal properties tend to have high values in residential real estate, because of the preferable aesthetic views and recreational properties. In the case of aquaculture, having polluting aquaculture facilities off of a coast is likely going to have a negative effect on real estate prices. The sole presence of an aquaculture facility may have a hedonic cost affecting the regional real estate that once had value from a vacant coast. By measuring one's willingness to pay for an aquaculture-free coastal region we can find a clear source of a monetary cost from pollution affecting markets.

This method for evaluating externalities has advantages in that estimations of hedonic prices are easily found based on consumer choices in the real estate market. Prices are easily compared across the housing market, which helps identify the monetary loss in environmental quality of a certain area. The limitations to this method are that housing markets are affected by unrelated factors like interest rates, population changes, and more. The reflection of the cost relies purely on real estate prices, which does not cover environmental damages outside of this measure.

Nonmarket Valuation III - Abatement and Replacement Costs Method

Abatement costs are often used as a method to determine monetary costs, because they assume the costs to producers to abate any damages on the environment are a useful estimate of the value of the environment (King & Mazzotta, 2000). Commonly, replacement and substitute costs can be used in addition to abatement costs to find a good estimation of external costs. In the case of aquaculture, this can be applied by looking at the costs to the firms to undertake methods of better husbandry to mitigate the polluting byproduct from aquaculture production. Another case using replacement costs would be measuring costs of restocking fish to replace the salmon populations lost to disease acquired from the farms.

The benefit with this method is it uses data that can be obtained from producers and hatcheries to determine costs associated with abatement/replacement. It bases its assumption on the use values to create a consistent value that can be substituted for costs that are difficult to value by any other means.

This method was used in an application by Liu and Sumaila in 2010. Liu and Sumaila used a procedure within this method called a joint-production approach. A joint-production model looked at two forms of output. In the case of Liu and Sumaila's work on salmon farming, the first form of output is the desired output of salmon and the second output is the socially undesired output of phosphorous and nitrogen pollution entering the ecosystem. This dual output is reflected in an example production possibilities frontier that depicts pollution increasing as there is more output of the desired good or service. Liu and Sumaila's research concluded that by using sea-bags for production to abate external costs, there would be a cost to the producers of about 5.5%-7.5% of revenue.

The joint-production technique is one form of valuing nonmarket damages that are associated with aquaculture. This method, however, does not capture costs of escaped fish, spread of diseases, and others. It purely captures the costs of pollution for the two pollutants. This valuation methodology alone does not capture the total external costs of production in salmon. This is a key flaw of using this method alone. The abatement costs in this method are derived purely from the sphere of production and are, in turn, used as a proxy for social costs. The benefits used to repair the damage do not always equal the costs and this is a major flaw in this method.

The abatement method does not take into account consumer preferences when determining the monetary cost of the externality and may also be flawed due to asymmetric information. Also, restocked salmon are not identical to natural wild salmon, and therefore, they are not exact replacements. Conservationists argue that restocked salmon do not have genetic survival instincts that wild salmon have and upon spawning, their future generations have higher mortality rates at young ages (Greenburg, 2010).

Nonmarket Valuation IV - Contingent Valuation

Finally, there is the contingent valuation method. This is a method in which the costs are analyzed by surveying society to determine how much they would be willing to pay to keep an environmental good or service or willing to accept compensation for the loss of an environmental good or service (Pearce & Turner, 1990). This reveals human preferences specifically to help determine monetary values of an environmental property. In the case of aquaculture, society could be surveyed as to how much they would be willing to pay for salmon to reach the maximum sustainable yield stock.

This method has many benefits, but also has many flaws. The main benefit from this method is that it captures more than just the use values for the environment, but it also captures nonuse values. Other benefits with this method are that it is also applicable to most environmental issues and is often the only method available. Societies' gross willingness to pay is considered to be the market price of the good (if available) plus any excess consumers benefit. Looking at Figure 11, we can see that the excess consumer benefit is the area AEP.

The contingent valuation method does have many limitations. People surveyed often are unsure how to monetize an environmental good or service. People taking surveys make hypothetical guesses as to their willingness to pay, but in an actual market may not make that same decision. There is also the risk that the survey may have biased wording of the questions. These limitations certainly cause uncertainty as to the accuracy of each survey.

Total Economic Value

A commodity as defined by Merriam-Webster's (n.d) dictionary is "anything useful or valued." By this definition, environmental goods and services like clean air are indeed commodities and deriving the demand for a commodity means understanding its total economic value. The total economic value for goods and services that are represented in a demand curve includes more than just the value gained from actual consumption of the good. The utility gained in consumption is referred to as use value. If the commodity is consumed, the use value becomes realized. Aside from a commodity's

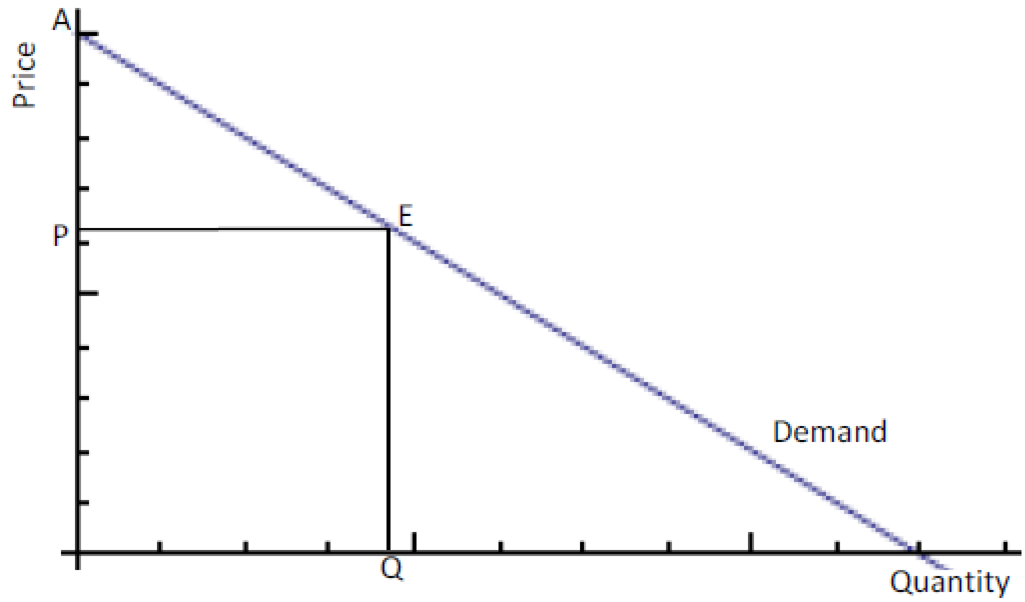

Figure 11: The curve labeled D represents a Marshallian demand curve where consumer income is held constant. EPQ represents the total revenue, which is the area below the market price and to the left of the market quantity. Consumer surplus is represented by the area AEP. The consumer surplus is a reflection of social welfare also known as utility to the consumers.

use value, there is also the commodity's intrinsic value. Intrinsic value is any value of a good or service that is inherent to a commodity that is any value outside of consumption (Pearce & Turner, 1990). The option value of a commodity is the commodity's trait that it has the option to be used by society (op. cit.). Society values the option to consume wild salmon or catch them in recreational fishing. There is also a factor of existence value, which is the value of a commodity just remaining in existence whether for reasons of inheritance or personal satisfaction (op. cit.).

It is important to capture the use value and the intrinsic value for the environmental goods that are affected by pollution. Wild salmon are still regarded as valuable as use values for their natural taste and also have valuable intrinsic components, as society values both the option to consume wild salmon as well as that their existence is valued for future generations. Salmon conservationists like NASCO reflect the existence value of wild salmon. All of these values must be captured in order to find an accurate total economic value for the damages caused by aquaculture. Market-price costs and contingent valuation are the two methods that reflect total economic value for goods since these costs are captured by looking at societies' preferences.

Policy Options

Once the environmental damage has been measured, it is up to policymakers to design and enforce regulations. The goal for policymakers to maximize social welfare can be achieved by three key policies: standards, pollution taxes, and marketable permits. Each of these policies has different benefits and limitations. This thesis aims at finding a policy that will maximize social benefit and is sensible to administer.

Standards may be the most common form of pollution regulation (Pearce & Turner, 1990). A standard is a level of allowable pollution that can result in penalties to polluters once the level has been exceeded. Standards may be set as an estimate of the assimilative capacity of an environment, but it seems more commonly that standards are set based purely on health and safety measures. Since standards are rarely based on economic conditions and welfare losses, they are often flawed and not set at the optimal level. Standards are also flawed because many producers will exceed the level of pollution, because the ability of administrators to enforce a penalty is not certain because of asymmetric information. This asymmetric information makes enforcement of a standard costly, since constant oversight of all polluters is very expensive and as a result, there is a natural tendency for polluters to defy the regulation. There is also little incentive for the polluters to abate pollution since they are allowed to produce all the way up to the limits set by the standards.

Taxing a marketplace is often associated with economic losses, but in the case of pollution taxes, taxing a polluter can create significant economic gains. In the case of a pollution tax, a polluter is likely to choose to mitigate their pollution if the cost to do so is less than the tax imposed for continuing to pollute. This method generates revenue for the administrators of the tax. Benefits and limitations for this method will be discussed in greater detail later on.

Marketable permits were created by economist John Dales in 1968 as a system to improve upon the standards system. In a marketable permit system, permits are issued to pollute a specified amount. Dales advanced this method to allow for the trade of permits on the open market. This method will be discussed in more detail later in this thesis.

METHODOLOGY

The drop of wild stocks in Scotland is apparent by looking at trends in historical data. Figure 12 shows the catch and harvest figures for Scotland from the period 2002 to 2007. The catch represents the number in 100s of salmon caught through the methods of fixed engine and net coble, which means by a vessel and a positioned net, respectively. The effort level is flattening out in recent years while the harvest continues to drop. This signal of a dropping wild stock is a key reason for investigating the level of recruitment in Scottish wild salmon stocks.

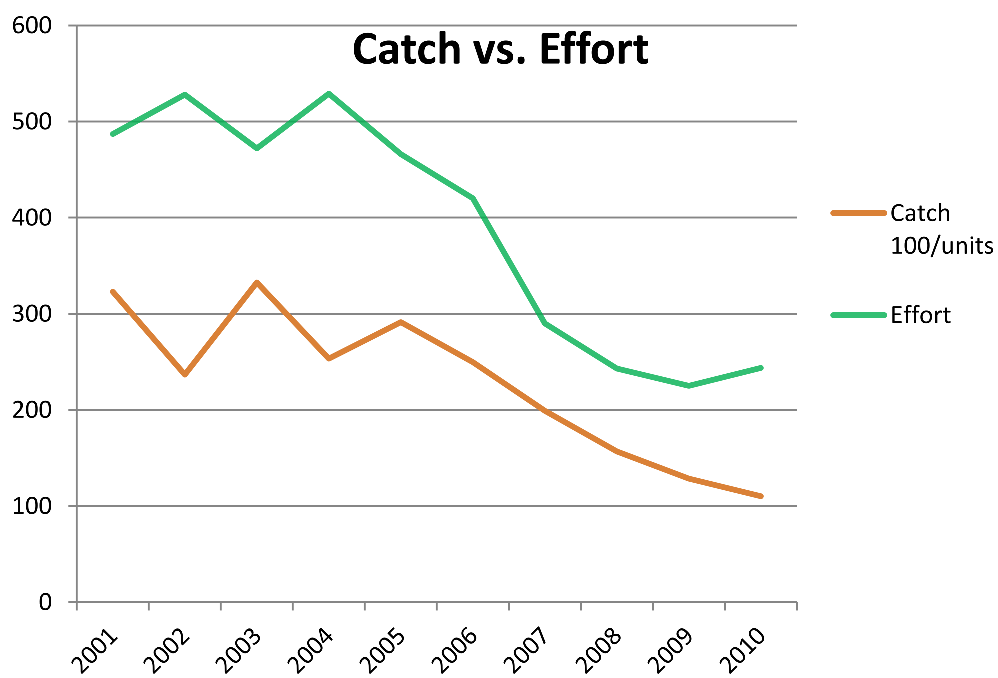

Figure 12: Catch vs. Effort in Scottish Fisheries. Data from FAO

Salmon have a unique development toward maturity, as we saw in Figure 1. Salmon pass through distinctive stages as they mature until they eventually reproduce. For a comprehensive understanding of how these life stages affect the recruitment for salmon, it is important to use an age-structured model to better understand the outcome of recruitment in salmon populations.

The four elements of recruitment - death, birth, immigration, and emigration - can be summarized in the Ricker Recruitment model:

$$R_{0.t+1} = R_{a,t}e^{\alpha(1-\frac{R_t}{\beta})} + (Im - Em)$$

The formula above is used to determine the expected biomass in the next period as a function of several parameters. $R_{0.t+1}$ is the number of salmon at age 0 in the next period (t+1). For salmon, since reproduction is annual, we can assume each period is 1 year. This is a measure of fry salmon. $R_{a,t}$ is the biomass of the current generation available to spawn at age a. This is also known as the "base" population. The intrinsic growth rate is denoted as α, and β is the carrying capacity of the environment. Im is the number of salmon immigrating and adding to a particular stock and Em is the number of salmon emigrating away from a particular stock. Salmon rarely immigrate or emigrate between stocks and so it is safe to assume the net effect for this migration between stocks is null. Salmon by nature remain in the stock to which they were born, so this assumption is true in regards to the species of salmon (OECD, 2004). This model for recruitment is especially applicable to salmon as salmon have a peculiar age-structured behavior that affects the size of future stock sizes. $R_{a,t}$ is age-structured in composition as follows.

$$R_{a,t} = N_{a-1,t} * s_a(1 - m_a)$$

The formula above determines the biomass of the spawning stock. $N_{a-1,t}$ is the number of fish in the previous period at age a-1. s_a is age-specific survival rate and $m_a$is age-specific maturity rate (rate at which salmon reaches a sexual peak) for the stock, and takes into account mortality from both natural causes and fisheries. Ultimately, some of the stock will be lost to mortality and some may not mature enough in the period to spawn.

Salmon's migratory and maturity characteristics, seasonal behavior, reproductive characteristics, and age-specific mortality are four key reasons it is important to use an age-structured model. Some parr migrate to sea each year to feed as smolt, but not all smolt return annually to reproduce. The migration of salmon depends on the maturity of the population and maturity is variable by age and ultimately effects the base population returning to spawn. The seasonal behavior in salmon is also a major factor in determining the base population since fishing season and spawning season occur annually for salmon in exactly that order. Since mature salmon are harvested on their migration back to spawning grounds, the base population is affected by the amount of fishing allowed in that season. The reproductive characteristics of salmon also affect the effective recruitment rate of salmon across different ages. Larger and older salmon have a higher rate of reproduction than younger grilse, as pointed out by des Clers. Therefore, a base population of older, larger salmon will yield a larger level of recruitment per individual spawner. Finally, morality is also age-specific in salmon. As pointed out, salmon have a very high natural mortality rate at younger ages that declines as they reach maturity. At older age, salmon are more desirable for fishing harvest, so therefore, the fishing mortality is higher at older ages, but nonetheless, the net effect of fishing and natural mortality is much greater in younger salmon than in adult mature salmon.

In 1993, a model was created on Scottish Atlantic salmon, applying the age-structured model for recruitment to determine the effects of disease mortality, by Sophie des Clers. At the time des Clers's model was created, sea lice were not a critical threat in Scotland, and researchers' estimates at that time varied from the current estimates. By applying a modification of des Clers's model to present day Scotland, we will get an accurate estimate of the damages fish farms have in communicating diseases to wild fish, as a result of the spread of sea lice.

The des Clers model established a clear outline of the age-specific survival and maturity rates as denoted in Table 1. The numbers included in the table are based on research estimates in 1993 on Scottish Atlantic salmon. All of the rates in Figure 14 are provided by des Clers.

The fry have a survival rate denoted as M_1, and those who survive the first year become parr 1 (as explained in the Literature Review, a "parr" is a young salmon that remains in fresh water that has not yet matured enough to leave the fresh water and feed at sea). Parr 1 that survive into their second year (Parr 2) have a survival rate denoted as M_2. In the salmons' second year, some of parr 2 may go to sea to feed and some remain in fresh water to become parr 3. The percent of parr that choose to go to sea and become smolt are denoted as have a maturity rate of Q_1. Smolts at sea face a survival rate of M_3 and some may then become grilse that season and return to fresh water, denoted as M_5. M_5 is considered to incorporate any fishing mortality, as fishermen typically harvest

Table 1		
Survival Life Stages	Abbreviation	Survival Rates
N - Number of Fry	M1	7%
Survival Parr per River Year	M2	50%
Survival Parr Post-smolt 1st Year at Sea	M3	15%
Survival Second Year to Spawn	M4	53%
Survival Griles to Spawn	M5	40%
Survival Salmon to Spawn	M6	20%
Maturity Life Stages	Abbreviation	Maturity Rates
Fraction 2+ Parr -> Smolt	Q1	26%
Fraction 3+ Parr -> Smolt	Q2	94%
Fraction Returning as Grilse	Q3	30%
Computation for Biomass	Abbreviation	Fry Biomass
No. of Eggs per Grilse	Eg	700
No. of Eggs per Salmon	Es	3000
Ricker Formula Parameters	Abbreviation	Parameters
Intrinsic Growth	α	1.34
Carrying Capacity	β	$1.46 * 10^{-6}$

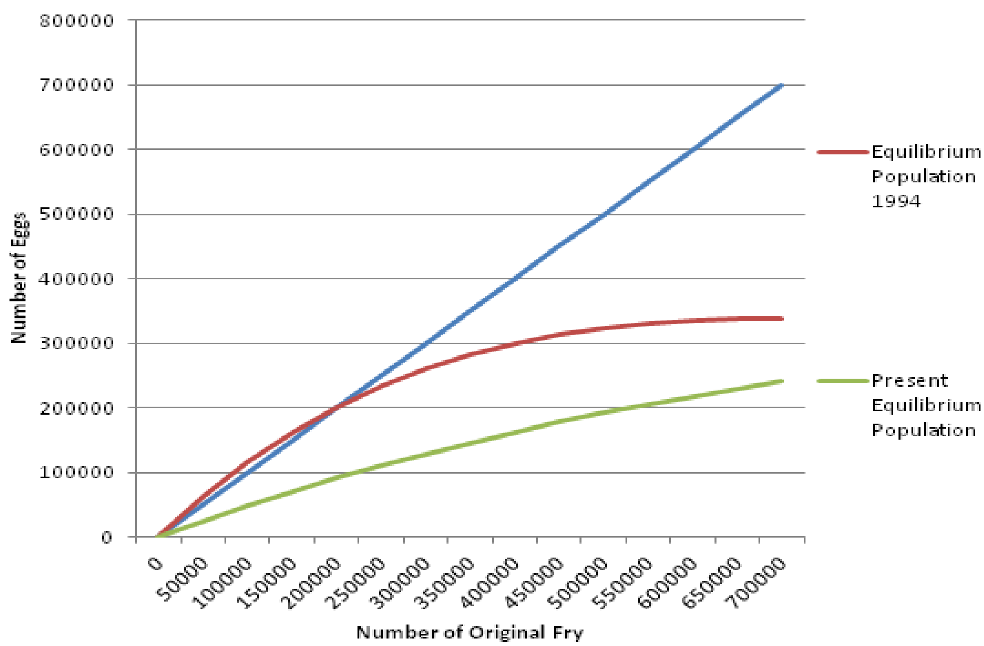

Figure 14: Results of modified recruitment using des Cler's data and adding in data from Krkošek et al.

fish while they are in their seasonal migration to spawning grounds. The parr 3 who remained in the freshwater lakes and have survived the year at the rate of M_2 may go to sea Q_2 or continue to remain in fresh water an additional year and become parr 4. There are very few parr 4 as most fish should have migrated to sea to feed by this point.

The smolts that have stayed an additional season at sea become full adult salmon. A full adult salmon is a smolt who remained feeding at sea two winters, whereas a grilse has only been feeding at sea for one winter. As the grilse and salmon return to spawning grounds, they lay E_g eggs and E_s, respectively, which are the reproduction rates estimated based on a 50% male to female ratio. In des Clers formula, E_g and E_s are used to convert individual members of the population to an estimated output of reproduced biomass.

Today, the salmon behavior is still similar in terms of egg numbers per fish and fractions of smolt staying at sea and fractions returning as grilse. We will update des Clers's model to account for modern research by updating mortality figures to account for additional mortality derived from aquaculture. The introduction of sea lice would lead us to changed parameters of mortality of M_1 reduced 60% and M_2 reduced 40%, as research estimates of mortality range from 40%-60% (Krkošek et al., 2007). In the former model, we see the level of replacement is achieved at 200,000 but, incorporating the disease-induced mortality leads to nonexistence of any level of sustainable replacement, as seen in Figure 15.

By analyzing the production levels for Scottish aquaculture, we can see that the growth has been substantial over recent years. Figure 15 shows the growth in UK tonnes of Atlantic salmon. Figure 15 includes a trendline that represents the 5 year moving average of production.

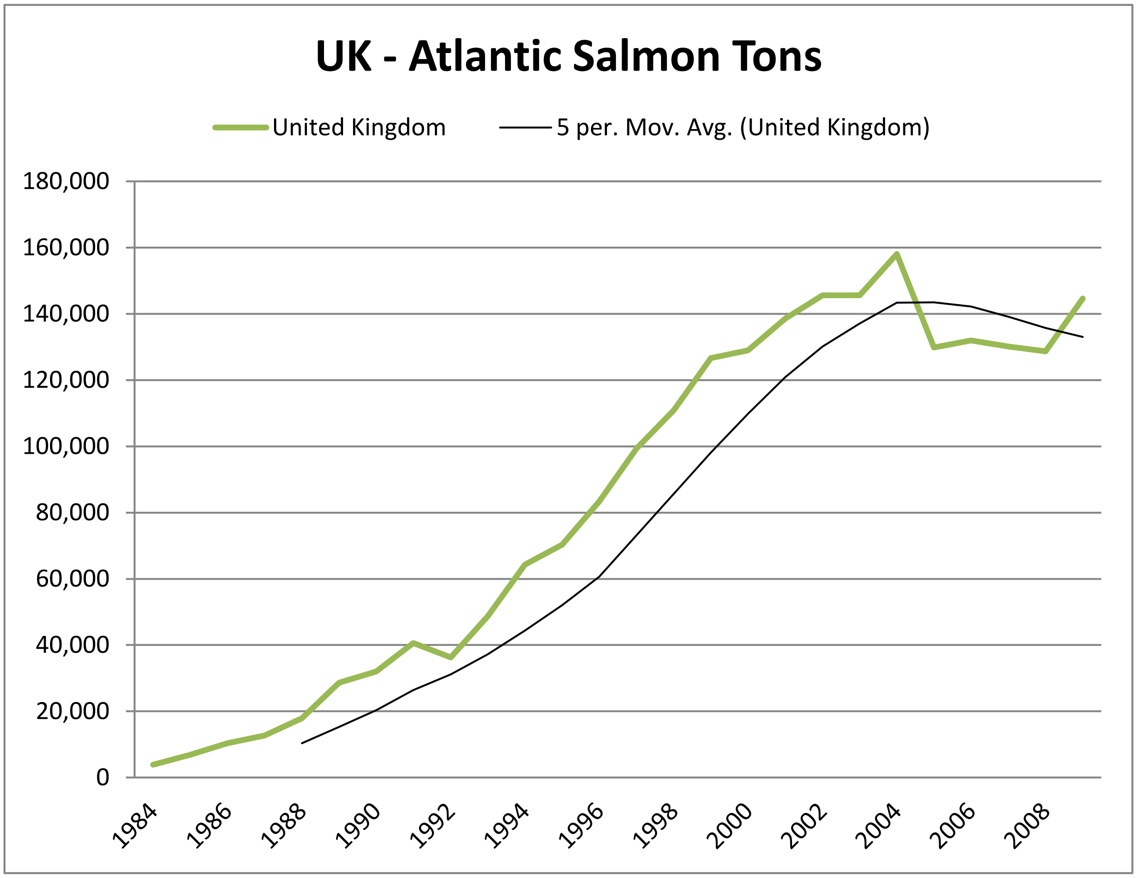

Figure 15: Data on UK salmon aquaculture production. Data collected from Eurostat

As Liu and Sumaila (2007) pointed out in the publication entitled "Can farmed salmon production keep growing?" Scotland is running low on space for aquaculture production. The 5-year moving average has been declining over the last 5 years. It appears as though Scotland is reaching maturity in the industry, as denoted in Figure 16. The steep drop in growth rate of the industry in Scotland indicates that Scotland's aquaculture is reaching a maximum. With resource extraction at its maximum level, it is important for Scotland to ensure the methods in production are sustainable for

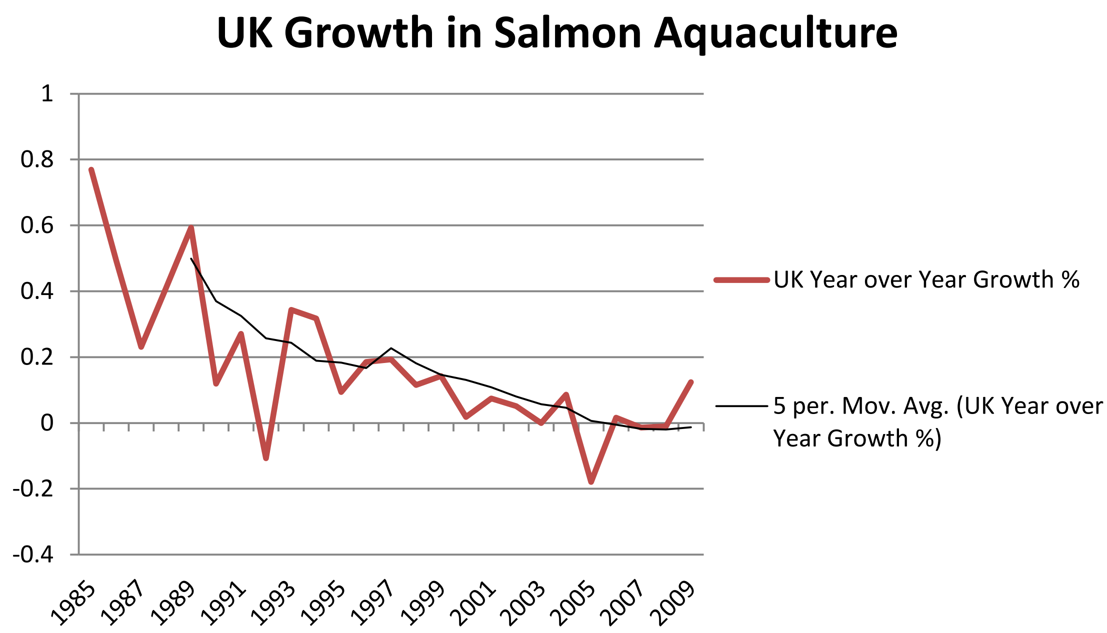

Figure 16: Data from Eurostat showing year over year growth and 5 year moving average

long-term profits. Scotland seems to be operating at the bounds of its production possibilities.

The changes in recruitment as presented in Figure 12 have significant economic effects. Applying monetary values to these effects is difficult, but we can estimate them in two ways. First, we will assess the costs using the market pricing method by evaluating the effect these costs have on relevant industries. Second, we will use the contingent valuation method to better capture the total social welfare that is lost.

First, it is important to identify who is being affected by the losses in recruitment. The first and foremost individuals affected by recruitment losses are regional commercial fisheries. Commercial fishery profits are dependent on sustainable stocks of salmon. Secondly, recreation anglers are affected as they too depend on sustainable stocks. Additional to effected recreational anglers are companies working in tourism that indirectly benefit from recreation anglers' success such as hotels, fishing guides, tackle dealers, and more. These groups depend on healthy annual salmon runs for their profit. The third group affected is the general public. The famous salmon runs have been a major part of Scottish culture for centuries. The general public values salmon for its existence as part of their heritage as well as their ability to bequest salmon to future generations of Scots. The commercial fisheries and recreation fisheries losses can be estimated using the market pricing method, but the general public's value for salmon can only be captured using the contingent valuation method.

By assessing the value of the industries affected from lost salmon populations, we can estimate the external costs that are present from aquaculture under the market pricing method. Researches in Scotland have periodically surveyed the recreational angling industry to try to get a valuation of recreational anglers and commercial fisheries. In 1982, the Scottish government estimated the expenditures from recreation anglers at £92 million (based on 2009 prices). This figure represents the presence of major externalities from aquaculture since it was prior to the aquaculture boom. The commercial fisheries expenditures in 1982 were not reported.

In 2004, Radford and Riddington re-evaluated the commercial fisheries and the recreational salmon anglers. The study by Radford and Riddington revealed that the commercial salmon fisheries were valued at approximately £1.1 million based on a catch of 72.9 UK tonnes. The recreational salmon angling industry generated approximately £61.6 million in expenditures in 2004. Commercial fisheries employed 502 full-time employees while recreational salmon anglers employed 2,723 full-time employees in 2004. Over 22 years, the recreational salmon angling industry lost £30.4 in expenditures due to the dwindling salmon populations. This is part of the costs of the externalities from aquaculture in its affect on recreational salmon angling.

If trends are to continue and a ban is to be enforced on commercial fisheries and recreational angling, based on Radford and Reddingtons' figures, the market price loss would be a £45.5 million economic loss from the complete ban on both industries. Of that loss, £34.5 million would be attributed to household directly and 1,966 full-time jobs would be cut. This is estimated based on a survey conducted across local anglers and anglers visiting from abroad. One hundred percent of anglers visiting from abroad, surveys revealed, would discontinue any angling in Scotland and a portion of local anglers revealed they would continue angling for different species. Based on the polluter pays principal, this £34.5 million economic loss from these two industries should be accountable to the damages from aquaculture producers.

A survey conducted over all of Great Britain tried to capture the willingness to pay to recover a 95% loss to wild salmon populations over the last 25 years. The survey revealed a willingness to pay £11.47 per household according to authors Lawrence and Spurgeon. The £11.47 per household equates to a present value of £4.5 billion or £180 million per year, which is roughly £15.5 million accounted proportionately to Scottish households. This method captured the perceived social costs that should be made payable by aquaculture producers. The Scottish farms recorded £53.7 million in revenues in 2011 according to the Scottish Salmon Producers Organization (SSPO). The revenues reported by SSPO are superficially high since they do not account for the welfare losses attributed to these costs.

DISCUSSION OF RESULTS

Figure 12 shows that Scotland's wild salmon population is dropping. The ongoing trend in the narrowing levels of effort and the drop in annual harvest levels is a clear indication the local salmon stocks are sliding. By analyzing the aquaculture-derived diseases in a model population of wild salmon, we can see the effects on the level of recruitment in a single lifecycle. Recruitment has fallen below replacement levels with the high mortality rates affecting juvenile fish. Aquaculture has not had this same mortality from sea lice as fish in the farms are typically mature. Scotland's dropping rates of production in the industry are a clear signal to take political action to prevent the damage from aquaculture for a sustainable future in the industry for aquaculture and fishing.

In aquaculture, there are a lot of methods to abate pollution. Liu and Sumaila (2010) suggest that by applying abatement, the damage resulting from the industry can be mitigated to sustainable levels for salmon to regenerate. Simple recommendations of reducing feed levels and better husbandry can make major improvements in the externalities affecting wild salmon where "better husbandry" includes techniques as simple as better maintenance of nets and treating sea-lice-infected salmon with cleansing baths rather than antibiotics. Disease-infected salmon should also be treated with target levels of antibiotics, with direct application performed on-shore. Aquaculture researchers also recommend letting farms lay fallow after the season to allow the local environment time to recover from the excess salmon waste.

Other abatement methods that have been suggested also include the introduction of feeder fish that are natural predators to sea lice. This will help reduce the levels of sea lice in the farm, and as a result, the farm will act like less of an incubating pool for sea lice. Also, by farming over seaweed beds or mussel colonies, the excess nitrogen can be absorbed by these natural filters rather than accumulate and cause a deadly algae bloom.

The location of fish farms has been a key part of their success. The farms' locations in sheltered sea waters has helped avoid natural destruction from strong winds and tides as well as naturally cleaning the farm with gentle currents. However, locations like fjords, lochs, and sea inlets are directly on the migratory path for salmon returning to fresh lakes to spawn or migrating back to sea to feed. This direct interaction is the cause of transmitted disease and also causes concerns of escaped fish as farmed salmon can join a wild colony immediately. By strategically finding locations away from salmon colonies, we can avoid these negative effects.

Policies

There are two common environmental policies that can be implemented to mitigate the social costs resulting from aquaculture. It is evident that the most effective policy would be one that is centralized and enforced on all producing nations. A centralized policy over all aquaculture production internationally is ideal in that its enforcement will reduce pollution to optimal levels of pollution as characterized by each producing region and individual firm. The policy implemented will not bar aquaculture, as it generates substantial benefits, but the policy would hold producers accountable for the levels of pollution or damage resulting from the production. The accountability enforced on aquaculture should be used to compensate those affected by the damages caused to create equity between producers and those affected by damages of production. This is part of the theory behind the "polluter pays principle" (Organization for Economic and Co-operation and Development [OECD], 2001). Salmon conservationists are one example of a group affected by the drops in wild salmon stocks. By compensating conservationists like NASCO (North Atlantic Salmon Conservation Organization) for the damages of aquaculture, there would be an inherent incentive for producers to abate. To best enforce this compensation, there are a number of methods. Marketable permits and a pollution tax are the two policies that will be reviewed for application in aquaculture in this thesis. As mentioned earlier, standards are often flawed for many reasons and are not considered to create an optimal economic level of welfare. Polluters will naturally disobey a standard since enforcement is extremely costly and in many cases, this cost is incurred by those in society who are affected by the negative external costs. Marketable permits and pollution taxes under a centralized policy are far more efficient to society.

Monetizing the total social costs from aquaculture is a rather difficult task. Monetizing costs is necessary to target ideal policies. In this case, there is a lot of opportunity in abating pollution, so the best method to reduce external costs is to enforce a policy that best promotes abatement of pollution in production. The goal with each policy is to find an optimum level of pollution. The Pareto optimum in pollution specifically from aquaculture is hard to calculate, because the external costs are difficult to monetize. Currently, there is a clear private benefit in aquaculture and that has been clearly apparent in its rapid growth. The current level of the private benefit is likely to be largely outweighed by its current level of external costs to the environment. Fortunately for aquaculture, there are a lot of good abatement methods that can be applied. Through abatement, we can maximize the total benefits received minus the sum of the environmental costs.

The first policy mentioned is a pollution tax. A pollution tax can be assessed on aquaculture producers based on their level of output of pollution. Pollution in this case can be considered any negative output associated in the production of salmon. A pollution tax assessed to the producers of aquaculture must be based on the amount of pollution emitted across various types of pollution (waste disposal, spreading of diseases, and escaped salmon). A pollution tax is estimated based on damage caused by polluting outputs at the optimal pollution level. As mentioned earlier, unlike most taxes that cause distortions, and hence losses to the economy, a pollution tax is used to correct externalities. The tax would be set at such a rate to make it cheaper for the firm to abate their pollution rather than forfeit the tax payment until the optimal level of pollution is achieved. For the tax to be optimal, revenues generated from the tax would be used to compensate those affected from the externality, like the recreational salmon anglers.

One benefit to a pollution tax is the ease of implementation in comparison to marketable permits. Legislators are more familiar with pollution taxes than marketable permits and are therefore more comfortable in enacting them. The pollution tax, however, has its faults. Estimating the damages of the pollution in monetary value can lead to disputes between central regulators and producers. Also, the tax may be too high and start to overly-restrict the economic benefits being derived from aquaculture.

The alternative to a pollution tax is the method of marketable pollution permits. As mentioned earlier, this is a method in which each firm must purchase permits for production of units of pollution. In aquaculture, the number of permits privately owned determines the allowable output of pollution of each firm. Since these permits are marketable, they can be bought and sold without restriction on a secondary market among producers and other members of society. If there are no restrictions to purchase a permit, this allows conservationists to enter the secondary market for the permits and bid to reduce pollution. Producers wanting to enter the market will have the option to purchase permits in the secondary market or invest in pollution-abating instruments in production.

Other benefits in the marketable permit system are the benefits to low-pollutant producers. If a producer has an advantage of being an efficient producer at low environmental cost, they can benefit by producing at a lower environmental/social cost. The method in determining how many permits would need to be sold in the primary market would be determined by targeting the optimal level of output. In the issuance process for permits, the central regulator can gain revenue by selling the permits in the primary market (i.e., directly to bidders). Heavy polluters are at a disadvantage in this system as they incur additional costs to acquire the permits and therefore, the advantage goes to firms who have mitigated or will mitigate their pollution.

Since the permits trade on the secondary market, the market will determine the market price for pollution. If the target output has been miscalculated and the damages of production are still exceeding benefits, regulators can take a number of steps to affect the permit market to achieve the optimum. Regulators can choose to buy permits on the secondary market as one option. Alternatively, regulators can choose to reduce the amount of pollution permitted by each permit, or revoke permits by law.

The marketable permit system can be difficult to enforce as it is costly to measure each firm's level of output, but this is also a negative feature in a pollution tax. In terms of aquaculture, the regulator would need to monitor pollution levels in many places around the world. Polluters who exceed their allowable level of production can be charged a penalty, but it is imperative that the penalty be serious enough to prevent any temptation to exceed their legal right to pollute. Each firm must be treated fairly so as to ensure the international system's effectiveness.

After reviewing both methods, I think that the marketable permits will promote the best pollution abatement practices. By creating a secondary market for pollution, firms will see natural incentives to reduce their pollution, and if they are unable to do so, they will be forced to exit the market as an uncompetitive producer. The concern of the high cost of pollution abatement does cause an imbalance in the international market at some level, as some nations may find higher levels of pollution to be less damaging. Authorities in the permit system may seek funding from primary issuance of the permits. The permit system may lead to producing better technologies as firms try to adapt for competiveness.

Valuing Costs for Optimal Policies

The earlier analysis on recruitment revealed the quantity of recruits of wild Atlantic salmon that are lost as a result of diseases derived from fish farms. The lost recruits reveal a lost economic quantity of wild fish, but unfortunately, the analysis makes no mention of the individual price for each lost recruit. Under the market-pricing method, the individual price per recruit is required to get an estimation of the external costs. Since salmon recruits are not traded on any world market, there is no clear market price. Salmon recruits have a value far different from a salmon that is sold for consumption which may be higher or lower. Since this market does not exist, the best method to estimate the damage function/external costs is going to be using contingent valuation to survey societies' preferences. The efforts made above in the methodology captured the United Kingdom's sentiment, but should be redone to purely capture Scotland's sentiment alone.

This is the simplest and only applicable method that can capture all of the external costs resulting from production. Contingent valuation can be used to capture more than the pollution affecting wild salmon, but can also can be used to capture the other types of pollution associated with aquaculture, like the escaping domesticated fish, the disposal of wastes, and the use of antibiotics. This is the best way to capture society's full sentiment on the external costs and gain an accurate derivation for implementing an approximately optimal policy.

It is important that in using this method, policymakers try to get as close to the actual damage function as possible in each regulated region. Surveys, therefore, must be administered regionally. Once a policy has been implemented, it is important that the damage function be re-evaluated continuously in the future to capture any changes in society's preferences, as well to make any changes *ex post* for any opportunities for Pareto improvements if the Pareto optimum is not met.

CONCLUSION

Scotland has enjoyed successes in aquaculture over the better half of a century, but it is now apparent that this practice may not be sustainable. Scotland may self-regulate its domestic farms, but the industry is connected internationally both in competition and in external costs. Salmon's migratory nature means a central regulator is needed to implement policies and oversight to reduce pollution to an optimal level. As a result of salmon's migratory behavior, the external costs of aquaculture are not only felt in the country of the polluters. External costs generated by producers in Canada can have negative effects on stocks in Alaska because of the interconnections of populations in the common feeding grounds in the Bering Sea, and expose other stocks to diseases.

Through abatement, we can continue to reap the benefits generated from aquaculture while limiting the costs. Scotland should try to reach an international agreement with other producing nations to create a marketable permit system to curb the negative effects from aquaculture. This would be in the best interest of all the producing nations in promoting the overall social welfare. The marketable permit system will help pollution be reduced to an optimal level and allow wild salmon stocks to recover from the excess mortality they are experiencing from diseases derived from the farms. This is the best way to preserve this delicate and precious resource while still balancing the benefits gained from aquaculture. There are many costs associated with aquaculture that cannot be monetized, and without strong oversight and good policies, those unmonetized costs may be realized in very negative ways with complete irreversibility in the damage.

Policymakers must take action quickly to maximize the total social welfare by finding the optimal costs of aquaculture.

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